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Monte Carlo simulations for angular and spatial distributions in therapeutic-energy proton beams

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ABSTRACT

The purpose of this study is to compare the angular and spatial distributions of therapeutic-energy proton beams obtained from the FLUKA, GEANT4 and MCNP6 Monte Carlo codes. The Monte Carlo simulations of proton beams passing through two thin targets and a water phantom were investigated to compare the primary and secondary proton fluence distributions and dosimetric differences among these codes. The angular fluence distributions, central axis depth-dose profiles, and lateral distributions of the Bragg peak cross-field were calculated to compare the proton angular and spatial distributions and energy deposition. Benchmark verifications from three different Monte Carlo simulations could be used to evaluate the residual proton fluence for the mean range and to estimate the depth and lateral dose distributions and the characteristic depths and lengths along the central axis as the physical indices corresponding to the evaluation of treatment effectiveness.

The results showed a general agreement among codes, except that some deviations were found in the penumbra region. These calculated results are also particularly helpful for understanding primary and secondary proton components for stray radiation calculation and reference proton standard determination, as well as for determining lateral dose distribution performance in proton small-field dosimetry. By demonstrating these calculations, this work could serve as a guide to the recent field of Monte Carlo methods for therapeutic-energy protons.

1. Introduction

Proton therapy has clear theoretical dosimetric advantages with Bragg peak (BP) dose distribution compared to conventional radiotherapy using photons. Its superior spatial dose distribution can deliver a high conformal dose to the tumor and spare normal tissue owing to sharper distal dose falloff ($l_{\mathrm{D80\text{-}D20}}$, defined as the length from 80% to 20% dose level) followed by BP. Currently, proton therapy delivery techniques trend toward making the proton beam smaller and using intensity-modulated and spot-by-spot approaches to improve treatment quality and efficiency and create new treatment capabilities for clinical therapy (Newhauser and Zhang, 2015; Pedroni et al., 2005). On the smaller lateral profile, better accuracy in simulation is desirable for lateral penumbra influencing dose detonation and conformity (Gelover et al., 2015). Furthermore, absolute proton dose determination in providing a reference beam usually demands perturbation corrections based on the Monte Carlo technique to determine the contributions from primary and secondary components, as to the photon primary standard (Lin et al., 2009). Moreover, Monte Carlo based treatment planning systems can be used to determine the configuration, and testing data for patient dose prediction relies on accurate simulations (Newhauser et al., 2007a). In addition, one of the clinical requirements is to use an independent tool to verify the correctness of the treatment plan. Therefore, a validated Monte Carlo system for the simulation of radiation transport could be a useful tool for pre-clinical and clinical research studies (Paganetti et al., 2004; Titt et al., 2008).

Before going into the clinical design of beamlines and treatment heads in proton facilities, it is important to understand the physics of a proton traveling through matter. In the traveling direction of the proton beam, the lateral variation in the transverse direction is affected by multiple Coulomb scattering (MCS) and the width of the proton beam spreads out with increasing depth. In addition to these elastic

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and inelastic Coulombic interactions, non-elastic nuclear reactions between protons and atomic nuclei induce secondary particles, for example, secondary protons. Along the track, the proton Bragg curve shows the fast descent characteristic at the end and that performance is used to avoid unnecessary doses to the rear tissues and organs. In essence, the accuracy of the calculated dose is directly affected by the physical model of multiple scattering in transport. The main MCS theories of the lateral dose variation with depth are Moliere theory and Highland's formula (Moliere, 1948). However, B. Gattschalk mentioned that Moliere theory may not be applicable at all in thicker materials (Leo et al., 1994; Gottschalk et al., 1993) and proposed a differential approximation to Moliere theory to predict the scattering power (Gottschalk, 2010) through a series of scattering angle measurements after protons hit different targets. Recently, proton therapy studies have revealed that MCS plays an important role in proton dose distribution around small implanted metal objects (Newhauser et al., 2007b). As we mentioned previously, common metal materials have been widely studied in both simulations and measurements of the thin target benchmark problem. However, the human body is approximately 70% water. In this work, a rare water thin target is devised to evaluate a downstream proton radial distribution and fluence halo (for the low-dose region from charged secondaries) component. In addition, the depth-dose distribution in a phantom with the recommended water material is also performed in Monte Carlo benchmark, and then beam characteristics are investigated to ensure the applicability of the model.

Consequently, this study aims to assess how different Monte Carlo codes perform in calculating the proton fluence and dose responses of given proton beams in the therapeutic energy range of 80–230 MeV. One aspect is to assess the angular distributions in the thin target problem including water and as control group aluminum. Specifically, we evaluated the contributions from proton primary and secondary components using the FLUKA, GEANT4 and MCNP6 codes. Furthermore, the water phantom case is used to analyze the differences in time consumption between the different Monte Carlo codes and employs a simple Gaussian method for precisely predicting the BP region distribution and features of the pristine Bragg curve that influence the treatment effectiveness. It is expected that the Monte Carlo calculations for the point and pencil proton beams could be used to predict further validation experiments, for primary proton and stray radiation evaluation, to determine the reference proton standard and for proton small-field dosimetry, which has become more important recently (Bednarz et al., 2010).

2. Material and methods

2.1. Simulation model

The proton source definition, interaction targets, tally region and tally variable were designed as shown in Table 1 and Fig. 1. A simple geometry was adopted for the calculations in all codes to obtain better

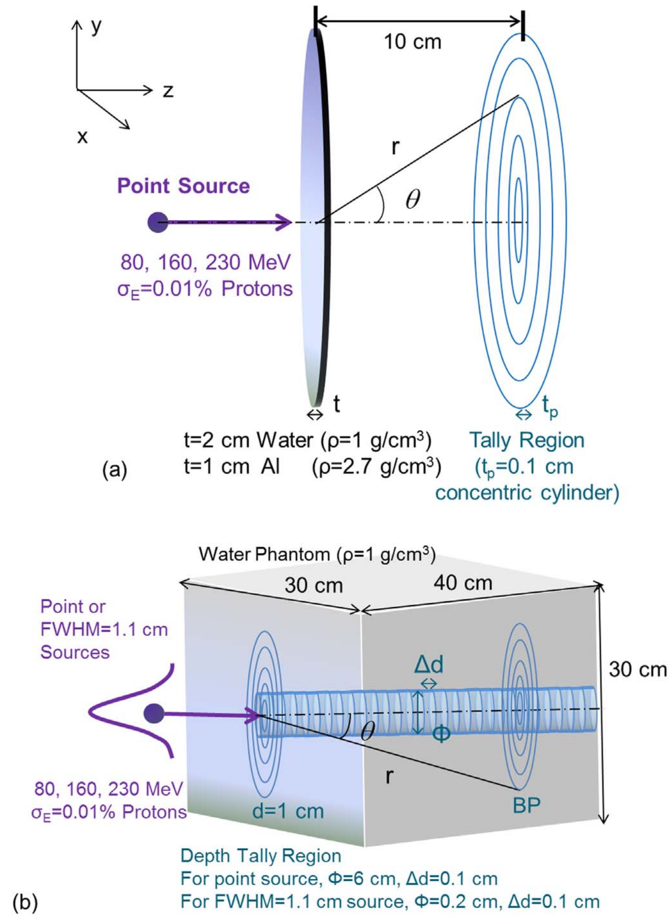

Fig. 1. Schematic drawing of the Monte Carlo model of (a) thin target and (b) water phantom.

calculation efficiency. The applied beam energies were 80, 160 and 230 MeV, which were selected based on common therapeutic energies and maximum machine energies. The energies of the protons were modeled with Gaussian distributions, with a full-width at half maximum (FWHM) of 0.01%. The initial direction of the source particles was parallel to the beam axis. Two simulated cases—thin target and water phantom—were devised for the Monte Carlo benchmark problem. In the first configuration, the point source passed through the 2 cm thick water and 1 cm thick aluminum targets. The tally region was located at the 10 cm downstream surface, and the lateral radial fluence was scored separately for the total, primary and secondary protons. In the second geometry, the other source type was described by Gaussian distributions with an FWHM value of 1.1 cm in the x and y directions entering into a 30×30×40 cm^3 water phantom. The spatial resolution of the tally was 1 mm in the z direction for simulations. The interval of the

Table 1
The proton source definitions, interacted targets, tally region and tally variable.

Proton Source		Target		Tally	
Energy (MeV)	Shape	Type	Shape	Type	Region
80	point	water target Al target	2 cm depth cylinder 1 cm depth cylinder	radial fluence	t_p = 0.1 cm, Φ_{max}=230.9 cm concentric cylinders at 10 cm plane away from target
160	point	water phantom	30×30×40 cm^3 cuboid	depth dose & fluence lateral radial dose & fluence	Δd=0.1 cm, Φ=6 cm cylinders in central axis at Bragg peak, t_p = 0.1 cm, Φ_{max}=6 cm concentric cylinders in central axis
230	FWHM=1.1 cm			depth dose & fluence lateral radial dose	Δd=0.1 cm, Φ=0.2 cm cylinders in central axis at d=1 cm & Bragg peak, t_p = 0.1 cm, Φ_{max}=12 cm concentric cylinders in central axis